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EVALUATION OF SMOKE AND GAS SENSOR RESPONSES FOR FIRES OF COMMON MINE COMBUSTIBLES

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Abstract

Experiments were conducted to evaluate the response characteristics of commercially available gas, smoke, and flame sensors to fires of common combustible mine materials. The experiments were conducted in the large-scale Fire gallery located at the National Institute for Occupational Safety and Health (NIOSH) Lake Lynn Laboratory (LLL) in Fairchance, PA, using Ponderosa Pine, Red Oak, Douglas-fir, high and low volatile coals, PVC and SBR conveyor belt, No. 2 diesel fuel, and diesel exhaust. All the experiments (except those using No. 2 diesel fuel and the diesel exhaust tests) were conducted in a similar manner, with combustible materials heated rapidly by electrical strip heaters producing smoldering fires that quickly transitioned into flaming fires. The sensors included a diffusion-type carbon monoxide (CO) sensor, photoelectric- and ionization-type smoke sensors, a video smoke/flame detector, and an optical flame detector. Simultaneous measurements were obtained for average gas concentrations, smoke mass concentrations, and smoke optical densities in order to quantify the levels of combustion products at the alert and alarm times of the sensors. Because the required sensor alarm levels are 10 ppm and 0.044 m^{-1} optical density for CO and smoke sensors, respectively, the different sensor alarms are compared to the time at which the CO and smoke reached these alarm levels (1). In addition, the potential impact of using smoke sensors that have met the performance standards from accredited testing laboratories is also evaluated using the response of an Underwriters' Laboratory (UL)-approved combination photoelectric/ionization smoke detector. The results are discussed relative to fire sensor needs that can have a positive impact on mine fire safety.

Introduction

From 1990 through 1999, there were 87 fires in U.S. underground coal mines, resulting in 34 injuries (2). Preliminary analysis of Mine Safety and Health Administration (MSHA) mine accident investigation data indicates a total of 75 underground coal mine fires from 2000 through 2009, resulting in 10 injuries and 2 fatalities. In order to improve the level of fire safety and to guard against the disastrous consequences that can result from mine fires, federal regulation mandates the use of automatic fire detection in certain underground locations, such as conveyor belt entries, diesel fuel storage areas, and power centers (3). Clearly, life safety is critically dependent upon the adequacy of these gas and smoke sensors

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to provide for early-warning detection for a broad range of fires that are possible. In order to address this need, research was undertaken to evaluate and compare both smoke and gas detection devices that are commonly used in mine monitoring systems. Experiments were conducted using a wide range of common combustible mine materials to measure the performance of these devices to both non-flaming and flaming fires in order to determine their suitability for early-warning fire detection.

It is known that the two most common types of smoke sensors, photoelectric-type and ionization-type, respond differently to flaming and non-flaming fires due to their different operating principles. Photoelectric-type smoke sensors generally work on a light-scattering principle where, typically, a light-emitting diode (LED) is projected across an open cell and a detector located at an angle on the opposite side measures the light scattered when smoke particle aggregates enter the cell. In the typical design of ionization-type smoke detectors, a radioactive material is used to generate ions in the air space between two electrodes, and the potential difference of a third collection electrode, which is placed in between the first two electrodes, is measured. When smoke aggregates enter into the air space between the electrodes, the ions attach to the aggregates, resulting in an increase in the potential difference at the collection electrode. For ionization-type smoke sensors, the sensitivity decreases as the particle size increases, opposite to the behavior of photoelectric-type sensors.

Research conducted by NIOSH and others has revealed the importance of early-warning fire detection techniques and recommended a range of sensor criteria that will maintain the required sensitivity without interferences from other sources (4,5,6). These sources can include, but are not limited to, diesel exhaust, methane, humidity, coal dust, and other gases that may be produced during the combustion process. Some of these interferences, such as diesel exhaust and coal dust, have been studied extensively for their impact on mine fire sensors.

In order to better evaluate the performance of gas and smoke sensors, it is important not only to understand the smoke particle properties produced from the burning of common mine combustibles, but also how the levels of smoke and CO relate to each other for the different types of fires that are possible. Detailed quantitative data on smoke aggregate properties can be found elsewhere (7). The relative levels of smoke and CO produced from the different fires can also provide important indications as to the best type of sensor to be used for certain applications. It is also important to note that gas and smoke sensors used for fire detection in underground U.S. coal mines are not required to meet or exceed any consistent set of standard performance tests. Some sensors are approved by MSHA based solely upon the characteristics of electrical permissibility or intrinsically safe electrical equipment. For CO sensors, this procedure does not represent a significant problem, since CO sensors are required to alarm at specific levels of CO (ppm). For smoke sensors, however, the respective alarm levels are set individually by each manufacturer without the devices undergoing any standard performance testing. As a result, the relative levels of smoke at which the sensors alarm can have significant variations that can drastically affect their early-warning capabilities. To address some of these issues, this paper describes the results of large-scale experiments that were conducted to evaluate the adequacy of smoke and gas sensors that are commercially available to the mining industry and to present additional data on the properties and levels of CO and smoke produced from a variety of combustible mine materials.

Experimental Procedure

Fire gallery and experimental setup

Large-scale experiments were conducted in the Lake Lynn Laboratory (LLL) fire gallery, Fairchance, PA, shown in Figure 1. The fire gallery is constructed of masonry block walls, an arched steel roof, and a concrete floor. The interior walls and roof are coated with a fire-resistant cementitious coating and the cross-sectional area of the gallery is 7.5 m^2. A total of seven combustible materials were used in the experiments as received: Pittsburgh seam coal (high vol A bituminous coal lumps), a mixture of Upper Freeport and Lower Kittanning seam coals (low vol bituminous coal lump mixture), Douglas-fir (2 in × 4 in pieces), Ponderosa pine (2 in × 4 in pieces), red oak (2 in × 4 in pieces), No. 2 diesel fuel, and two different types of fire-resistant conveyor belts known generically by their primary polymer component as styrene butadiene rubber (SBR, 3 ft pieces) and polyvinyl chloride (PVC, 3 ft pieces). In addition, tests were conducted to determine the sensor responses to contaminants produced by the exhaust of a diesel engine.

To generate a smoldering-type fire, eight electrical strip heaters were embedded in each material. The experimental setup used for wood and coal is shown in Figure 2. The strip heaters were rated at 1500 W at 120 V producing a maximum surface temperature of 650 °C (1200 °F). The diesel fuel was ignited using a 1380 Kpa (200 psi) propane gas burner.

In order to measure the O_2, CO, and CO_2 concentrations, a gas sample averaging probe was positioned at the tunnel exit, 12 m downstream from the fire location, as shown in Figure 3. This probe was constructed from a 5-cm-diam steel pipe and had four inlet ports spaced at equal increments along the pipe. A small fan was located upstream of the fire to transport the combustion product gases and smoke from the fire to the tunnel exit.

The CO was measured using an Interscan Corporation RM series Rackmount Monitor with a sensitivity of 0 to 100 ppm and an inline filter to eliminate interference due to other gases, dust particles, and aerosols. Before each experiment, these gas analysis instruments were calibrated for both zero base line and span, and the gas travel times through the sample lines were also measured for use in correlating time-dependent concentration and alarm calculations. All sensor outputs were connected to a computer through an electronic processer for data acquisition. In addition to the gas analysis, two smoke obscuration meters were placed 12 m downstream from the fire location, 0.6 m from the tunnel roof, to measure the light obscuration at wavelengths of 635 nm and 532 nm. A separate gas sample was also extracted from a point just beyond the obscuration meters and flowed to a TSI DustTrak for simultaneous measurement of smoke mass concentrations. In addition, video cameras were located 6 m upstream and 4.6 m downstream of the fire to allow researchers to view the fire from two different vantage points.

Gas and smoke sensors

The sensors evaluated in this study included photoelectric- and ionization-type smoke sensors, a diffusion-type carbon monoxide (CO) sensor, a video smoke/flame detector, and an optical flame detector. Because smoke sensors, in particular, are not required to meet any performance standards, the response times of a UL-approved combination photoelectric/ionization smoke detector that has met rigorous UL performance standards were compared to response times of the Commercially-Available smoke sensors, demonstrating the improvement in early-warning capability when performance standards are used. The smoke sensors and the CO sensor are shown in Figure 3. Each of these sensors will be discussed in detail below.

The Spero sensor (S1) is an ionization-type smoke sensor that uses Krypton 85 to ionize the air space between two electrodes. It has been approved in South Africa for use in underground hazardous locations, and is commonly used for fire detection in South African mines. It is not approved for use in U.S. underground coal mines. The Smoke Boss (S2) sensor is manufactured by Reltek, Inc. It uses an optical light transmission technique to measure smoke levels and is approved by MSHA for use in U.S. underground coal mines. One of the claims made by the manufacturer is that unlike most smoke detectors that have only on/off alarms and are incapable of reporting gradually changing smoke levels, this sensor can monitor a gradual change of smoke levels. The Conspec smoke sensor (S3) is an ionization-type smoke sensor which is also approved by MSHA for use in U. S. underground coal mines. This sensor uses a source of Americium 241 to ionize the air space between two electrodes. The manufacturer claims that it is reliable, efficient, and able to withstand harsh conditions in underground mines. The VESDA (S4) is a highly sensitive photoelectric-type smoke detector, which claims to respond well to smoke from non-flaming, smoldering fires. Because it contains an internal pump, this sensor can convey air samples from several distant (up to 100 m) locations to the sensor to provide extended area coverage. This sensor has not been approved by MSHA for use in U. S. underground coal mines. A combination optical and ionization smoke detector, approved and listed by UL but not approved for use in U.S underground coal mines, was also used in this study. This detector, described in greater detail by Litton (8), was used in this study to compare the responses of the two types of conventional smoke detectors (photoelectric- and ionization-types that have passed rigorous performance standards) to the responses of the smoke sensors tested here that have not passed any uniform set of performance standards. Lastly, the Conspec CO sensor (S5) is a typical diffusion-type electrochemical gas sensor and is approved by MSHA for use in U.S. underground coal mines. It is capable of measuring 1 ppm of CO with an accuracy of ±0.1 ppm. The electrochemical sensing cell is made by CitiTech, Inc., of the U. K.

In addition to the above point-type sensors, the response of a smoke/flame video monitoring system manufactured by AXONX (S6) was also evaluated. This video imaging system uses changes in light contrast to detect the presence of smoke liberated during the early stages of a smoldering fire. In addition, this system can also detect the onset of flaming combustion.

Results and Discussion

Table 1 shows the time to visible smoke and flame and the sensor alarm times for each material tested, for all the evaluated sensors in this study. The table also shows the time for the bulk average CO concentration, as measured at the end of the tunnel with the gas averaging probe, to reach 10 ppm. Irrespective of the combustible materials used, all the sensors alarmed after the onset of smoldering, but only some of the sensors alarmed before onset of the flaming stage.

As evidenced in Table 1, all of the combustible materials produced visible smoke within 4 minutes from the time that electrical power was supplied to the strip heaters. All of the materials, with the exception of the PVC belt, which generated only non-flaming smoke, reached flaming combustion between 13 and 24 minutes. Of the solid combustibles tested, the SBR belt and mixture of Lower Kittanning and Upper Freeport coal took the longest times to ignite. Of the four smoke sensors, only the VESDA and Conspec alarmed in all the experiments. The VESDA in particular, was found to be extremely sensitive to smoke. The Smoke Boss only alarmed during the SBR and PVC belt experiments, but did not alarm when burning any of the other combustible materials, including both types of coal. The Spero sensor alarmed only for the burning SBR belt and Douglas-fir. The UL-approved combination sensor reached the ionization alarm threshold in all the experiments, while the optical alarm threshold was reached in all experiments except for the low vol coal mixture and the diesel exhaust. Both of these experiments produced smoke with very low optical densities. The AXONX smoke/flame video detection system was also found to be very sensitive for all the materials.

In considering the above results, it should be noted that because the AXONX is an optical system that requires line-of-sight operation, its use underground may be limited to protection of local areas with high risk of fire such as belt drives and storage and maintenance areas. In addition, photoelectric-type smoke sensors are generally known to be more sensitive to non-flaming smoke than flaming smoke, while the reverse is true for ionization-types.

This latter behavior is readily apparent when comparing the earlier response times of the VESDA smoke sensor (photoelectric-type) to the later response times of the Conspec smoke sensor (ionization-type), and also the relative optical and ion response times for the UL-approved combination. The CO sensor always alarmed after the smoke sensors alarmed, indicating that CO sensors are generally not as sensitive to the early stages of a developing fire as smoke sensors. There was very little time difference between the Conspec CO alarm and the time that the bulk average CO reached 10 ppm. Figure 5 shows the maximum CO concentrations and the maximum optical densities observed at 532 nm for each combustible material used in these experiments. The diesel fuel fires and conveyor belt fires produced the highest smoke concentration, while the lowest optical densities were recorded for the diesel exhaust and low vol coal. One important point to note here is that the Smoke Boss alarmed only at high optical densities produced from the conveyor belt fires.

This is a much higher optical density than the MSHA-regulated 0.044 m^{-1} optical density level, a drawback that would need to be addressed before this sensor could be used effectively in underground mines. The highest concentration of CO was observed when burning Douglas-fir, while the lowest CO concentrations were obtained with Pittsburgh seam coal, the low vol coal mixture, and diesel exhaust. It is also interesting to note that both types of coal produced similar CO concentrations but two significantly different smoke optical densities. This latter result would tend to indicate that the two types of coal may have different chemical and physical properties.

Experimental data

Figures 6–11 illustrate how the levels of CO and smoke varied with time for several of the combustible materials used in these experiments, the time when visible smoke and flame occurred, and with the times at which the respective sensor alarms were activated. Sensors S1 to S7 are identified in the "Gas and smoke sensors" section, with black vertical lines followed by the sensor symbols representing the alarm times for that particular sensor. The CO analyzer data corresponds to the bulk average CO.

Figure 6 shows the results of the experiment with Pittsburgh seam coal. In this experiment, the AXONX video smoke detector (S6), the VESDA (S4) smoke sensor, and the Conspec smoke detector (S3) alarmed during the early smoldering stage. Immediately after visible flames were observed, the Spero sensor (S1) and the flame sensor alarmed. This typical sequence of alarms reinforces the fact that photoelectric-type detectors (S4) are more sensitive to smoke from smoldering fires while ionization-type smoke detectors (S3) are more sensitive to smoke from flaming fires. The Smoke Boss (S2), which is also a photoelectric-type smoke sensor, demonstrated a poor response, as noted above, probably because it operates on the principle of light extinction rather than light scattering. There is little or no difference between the roof CO concentration, as measured by the Conspec CO sensor, and the bulk average CO concentration during the early non-flaming stages of the fire. This is primarily because there was very little increase in the temperature of the combustion products; therefore the buoyancy effects leading to stratification near the roof were not significant and the combustion products tended to move slowly as a "plug" down the tunnel.

Figure 7 shows the data obtained for a mixture of Lower Kittanning and Upper Freeport coal mixture (low vol coal mixture). The percent volatility for this coal was about 20% compared to about 40% volatility for Pittsburgh seam coal. This difference in volatility appears to have a major impact on detection, since only the VESDA (S4) and the AXONX (S6) smoke sensors alarmed in this test. Both the smoke mass concentration and smoke optical densities were much lower for this lower volatile coal compared to those values obtained for the higher volatile Pittsburgh seam coal, although the CO levels are quite similar. The Conspec CO alarm was reached shortly after visible smoke was observed. The smoke optical density never reached the 0.044 m^{-1} alarm level, and only reached 0.019 m^{-1} in about 1–2 minutes after visible flames were observed. These results may be related to the physical and chemical properties of the low vol coal compared to the more volatile Pittsburgh seam coal, but further investigation of this phenomenon is beyond the scope of the project.

Figure 8 is the experimental data obtained for Red oak. The AXONX (S6) and VESDA (S4) sensors alarmed very quickly after visible smoke was observed followed by the Conspec smoke sensor (S3). Just as for the experiment with Pittsburgh seam coal, the Smoke Boss did not alarm. The results obtained using Douglas-fir and Ponderosa pine are very similar to the Red oak experimental results but are not shown here. Similar to the Pittsburgh seam coal experiment, data from the Red oak experiment show that both the bulk average CO concentration and the Conspec CO concentration near the roof reached their 10 ppm CO alarm thresholds in ~7 to 8½ minutes. It is worth noting that in all the wood experiments, the smoke optical density alarm level of 0.044 m^{-1} was reached earlier than the 10 ppm CO alarms. Compared to the coal experiments, Red oak produced significantly higher concentrations of both smoke (30 mg/m^3) and CO (35 ppm) before visible flames were observed.

Figures 9 and 10 are the data obtained for the PVC belt and SBR belt, respectively. Both experiments produced high levels of smoke (>30 mg/m^3) with optical densities greater than 0.2 m^{-1}, and the PVC belt did not reach flaming combustion during the experiment. The AXONX (S6) and VESDA (S4) sensors alarmed shortly after visible smoke was observed, while the Conspec smoke sensor (S3) took another 4 minutes to alarm. As mentioned previously, the Smoke Boss (S2) alarmed only during the conveyor belt fire tests. For these two tests, the average alarm time was about 11 minutes after power was supplied to the heaters, or 2 minutes before visible flames were observed. It is interesting to note that since there was no flaming during the PVC test, the average CO and roof CO levels tracked each other very well since there was no stratification due to buoyancy effects. In both conveyer belt tests, the smoke optical density alarm level of 0.044 m^{-1} was reached much earlier than the 10 ppm CO alarm level.

Figure 11 shows the data obtained for diesel exhaust. During this test, high levels of CO were generated but smoke mass concentrations and smoke optical densities were found to be very low. Both the VESDA (S4) and the Conspec (S3) smoke sensors alarmed during the experiment, and the Conspec CO alarmed at 4 minutes, even though there was no fire. Given the fact that diesel exhaust is not a fire, a sensor should be able to discriminate between the smoke generated from a diesel exhaust and a real smoke/flame generated from a fire involving typical mine combustibles. None of the evaluated sensors were able to meet this criterion.

Comparison of Sensor Alarms to Major Events and Recommended CO and Smoke Alarm Levels—Figure 12 shows the overall performance of the sensors tested relative to the onset of visible smoke and visible flame. The x-axis denotes the time taken for each material to flame and the y-axis denotes the time that each sensor alarmed relative to the smoldering and flaming times of each material. Arrows indicate the materials tested. In this figure, the closer the alarm time is to the appearance of visible smoke, the earlier the alarm and the more time that would be available for evacuation during an actual fire emergency. As noted in Table 1, some of the smoke sensors did not alarm at all. Irrespective of the material used, the VESDA (S4) and AXONX smoke sensors (S6) alarmed first. With the exceptions of the Spero sensor (S1) and in two experiments the Conspec smoke sensor (S3), all the sensors alarmed before visible flames were observed.

Figure 13 shows the performance of the sensors relative to the 10 ppm Conspec CO alarm, irrespective of the materials used. The VESDA and the AXONX smoke sensors alarmed before the 10 ppm CO alarmed, while the Conspec smoke sensor alarmed before the 10 ppm CO alarm in only about half of the experiments. In general, the experimental fires took longer to produce the 10 ppm CO than to produce the 0.044 m^{-1} OD. This result is indicative of the observation that, even for these rapidly developing fires, smoke sensors have the potential to provide for earlier warning than CO sensors—a result that can have life-saving benefits. Even though the Smoke Boss alarmed only during the belt fires, when it did alarm the roof CO had not yet reached the 10 ppm alarm level. It should be noted that in all experiments the bulk average CO reached the 10 ppm alarm level before visible flames were observed. With the exception of the Spero sensor, the gas and smoke sensor alarms almost always occurred prior to the appearance of visible flames.

Figure 14 shows the times at which the smoke and the CO sensors alarmed compared to the times at which the optical sensor of the UL-approved combination photoelectric/ionization smoke sensor reached its alarm threshold. As shown in the graph, very few sensors alarmed before the optical alarm (even for the most sensitive smoke sensors tested, i.e., VESDA and AXONX). In all the experiments, the 10 ppm Conspec CO alarmed long after both the photoelectric and ionization sensors reached their alarm levels. In most of the experiments, it is also evident that the optical component of the combination sensor alarmed before the ionization component, which is in keeping with the general observation that the photoelectric-type sensor is more responsive to smoldering combustion than the ionization-type. These results indicate that a combination photoelectric/ionization smoke sensor could be an ideal candidate for in-mine use to detect smoke generated from both flaming and non-flaming fires. In addition, the uniformity of response of this sensor, for both the optical and ionization components, demonstrates the increased reliability that is possible when sensors meet performance standards.

Summary

Overall, the experiments conducted to evaluate Commercially-Available smoke sensors revealed that for the types of combustible materials typically found in underground coal mines, smoke levels develop earlier than CO levels and smoke sensors responded earlier than the CO sensor. Of the four point-type smoke sensors evaluated in this study, the VESDA and Conspec smoke detectors alarmed in all the experiments, irrespective of the material used. The Smoke Boss smoke sensor only alarmed when burning SBR and PVC belt and then only at very high smoke levels, while the Spero smoke sensor alarmed only when burning SBR belt, diesel fuel, and Douglas-fir. The AXONX video smoke/flame detection system also alarmed in all the experiments and the alarm times were very close to those of the VESDA. However, because of its principle of operation, this sensor may be better suited for use in more localized, high-risk areas, such as conveyor belt drives, fuel storage areas, or underground maintenance areas.

The data obtained for the UL-approved combination smoke sensor indicated a more uniform and consistent response than the other smoke sensors that were evaluated. This result would indicate that mine fire detection has significant room for improvement if smoke sensors targeted for use in underground mines were required to meet or exceed standardized performance tests as part of the MSHA-approval process. The MSHA regulations specify that the smoke sensors shall alarm at smoke optical densities no greater than 0.044 m^{-1}, but for these experiments this single alarm criterion was never met by any single smoke sensor over the range of combustible materials used in this study. This result only serves to reinforce the need for some type of performance standard. In particular, the performances of both the Smoke Boss and the Spero sensor were found to be grossly inadequate, either producing no alarm in many of the experiments or alarming only at high levels of smoke optical density.

Even though the 10 ppm CO alarms occurred slightly later than the 0.044 m^{-1} smoke optical density alarms in almost all of the experiments, it should be noted that not all combustibles used in the experiments produced smoke optical densities equal to or greater than the required alarm threshold. While the maximum optical densities measured for Ponderosa pine and Pittsburgh seam coal were very close to the alarm threshold (0.042 and 0.043 m^{-1}, respectively), the maximum value observed for the low vol coal was only 0.019 m^{-1}. While beyond the scope of this paper, the relative levels of CO and smoke obtained for the two coals used indicate that coal rank, or volatility, may be an important consideration in the selection and use of mine fire sensors and be worthy of further investigation.

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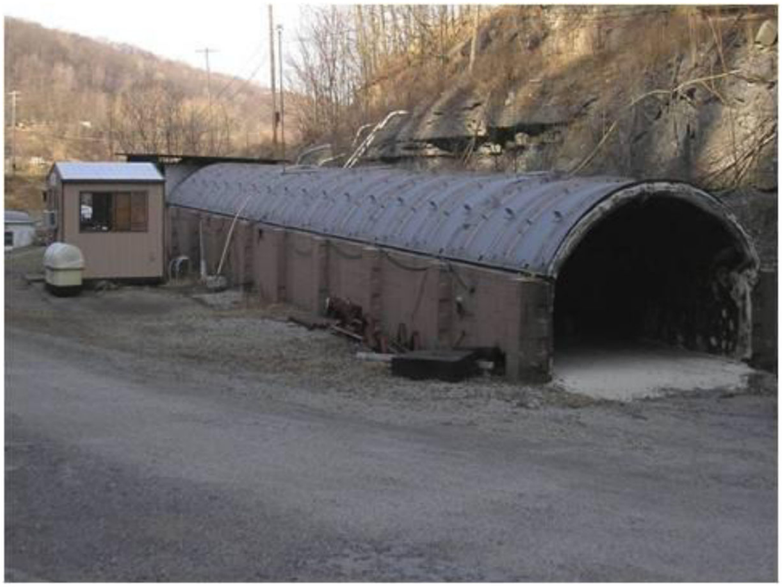

Figure 1.
Lake Lynn Laboratory fire gallery

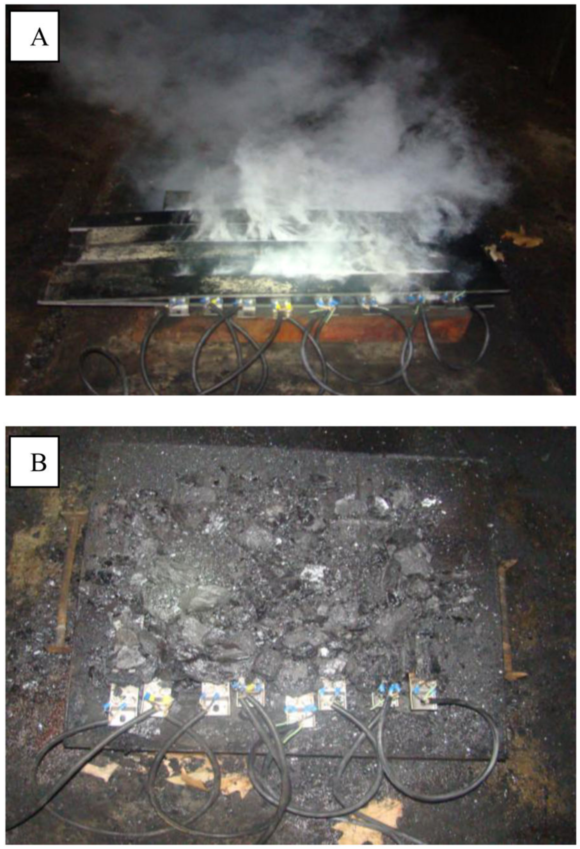

Figure 2.
Experimental setup with heaters embedded in (A) smoldering wood and (B) coal.

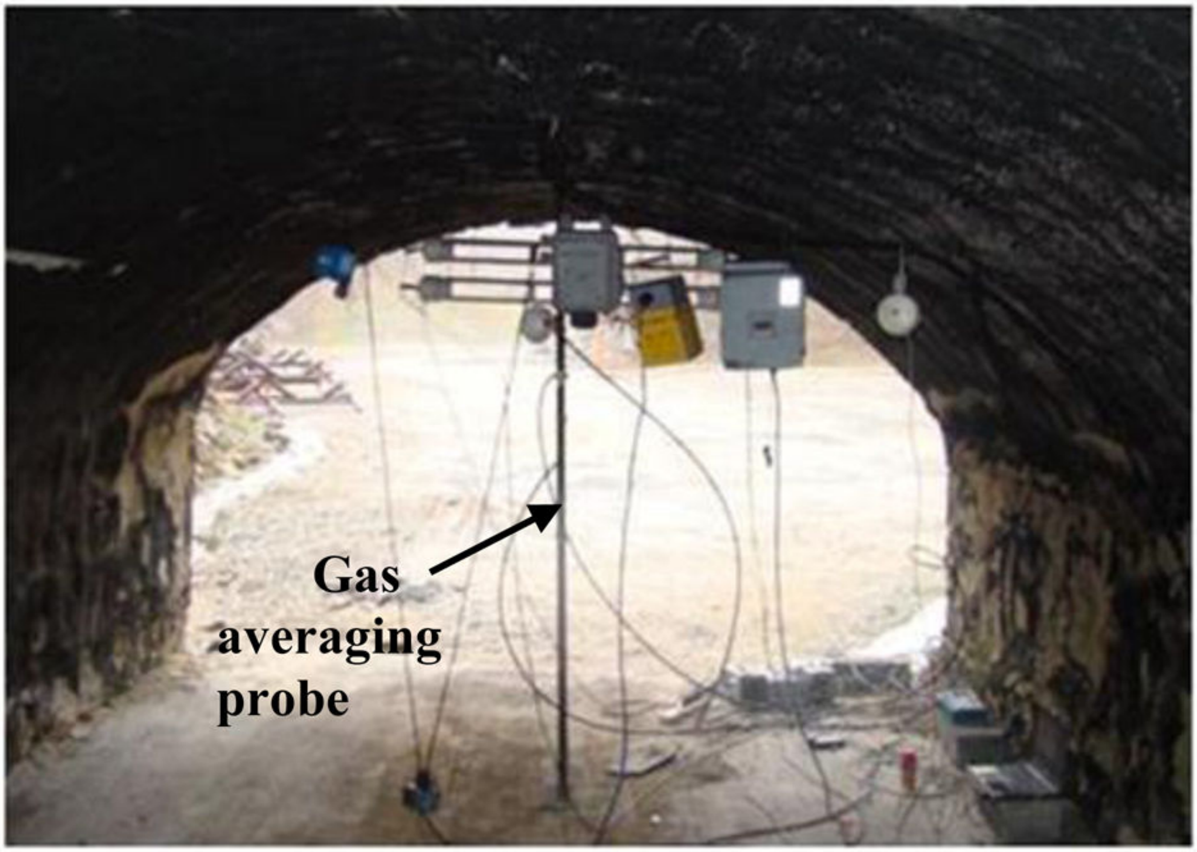

Figure 3.
Gas averaging probe at the tunnel exit and sensors mounted near the roof.

Figure 4.
Sensors used in this study.

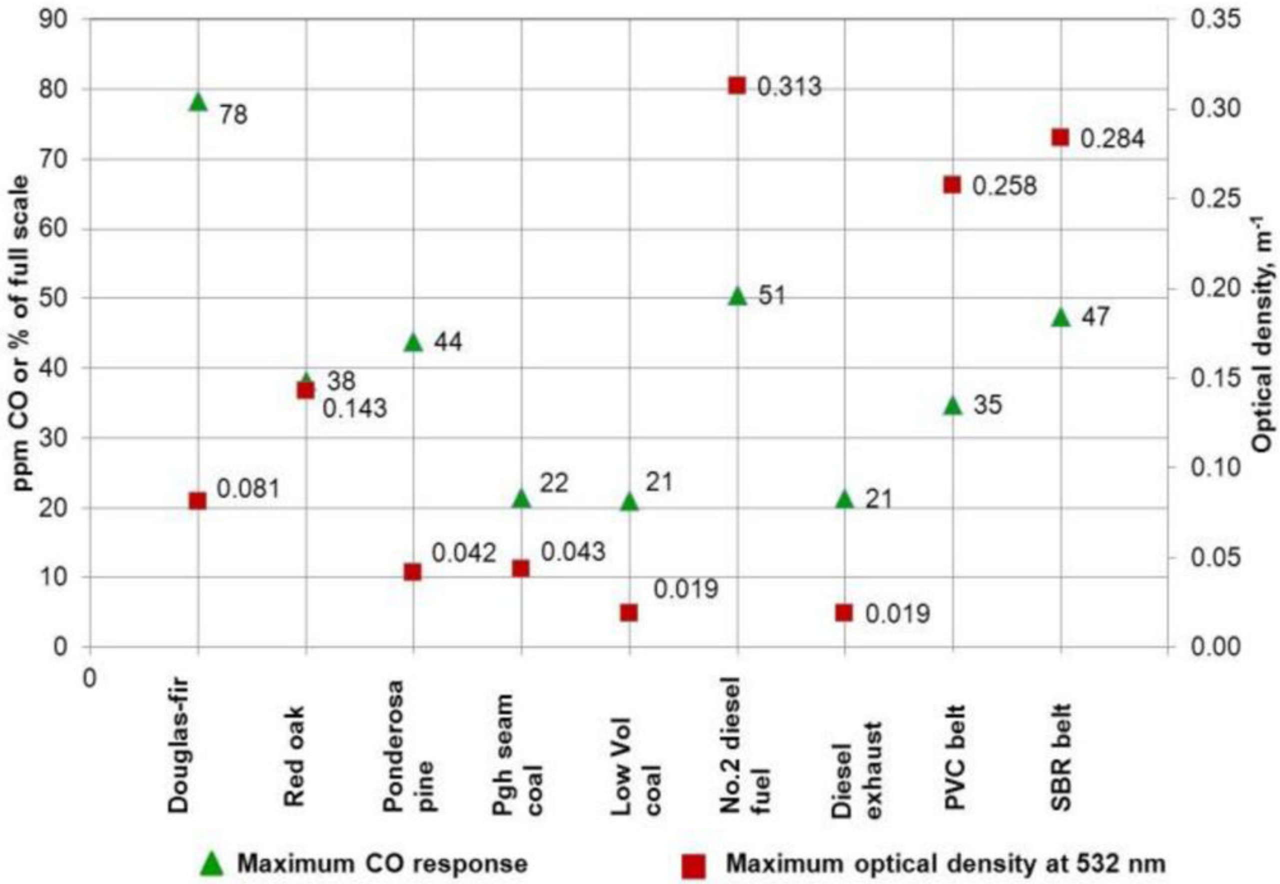

Figure 5.
Variation of maximum average CO peak and smoke optical densities for the different combustible materials used in these experiments

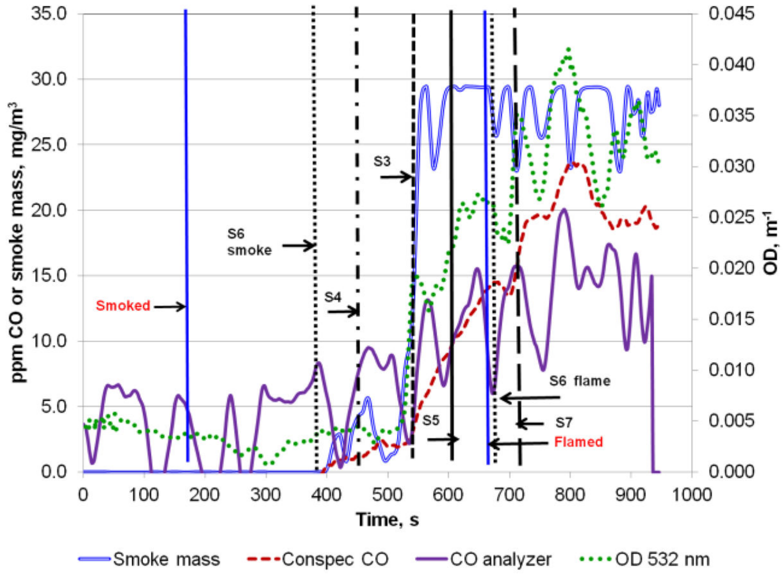

Figure 6.

Comparison of sensor alarms to smoke and CO concentrations for Pittsburgh seam coal-2.

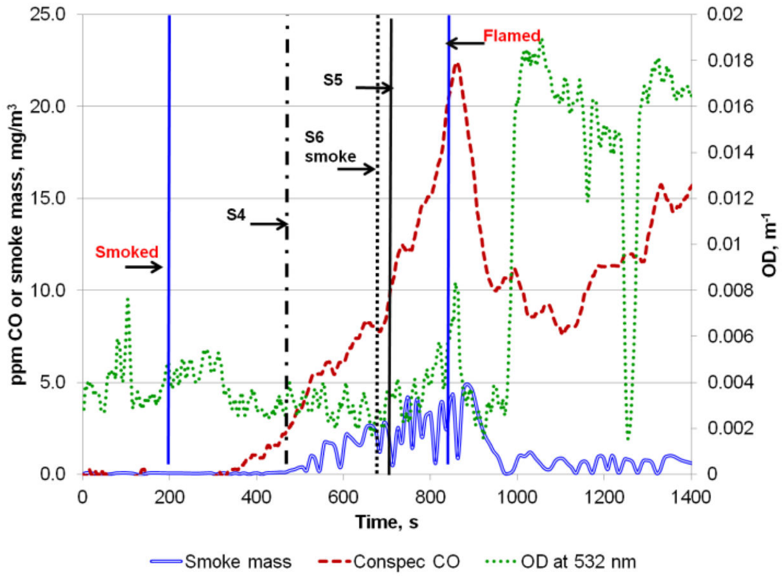

Figure 7.

Comparison of sensor alarms to smoke and CO concentrations for low vol coal mixture-1.

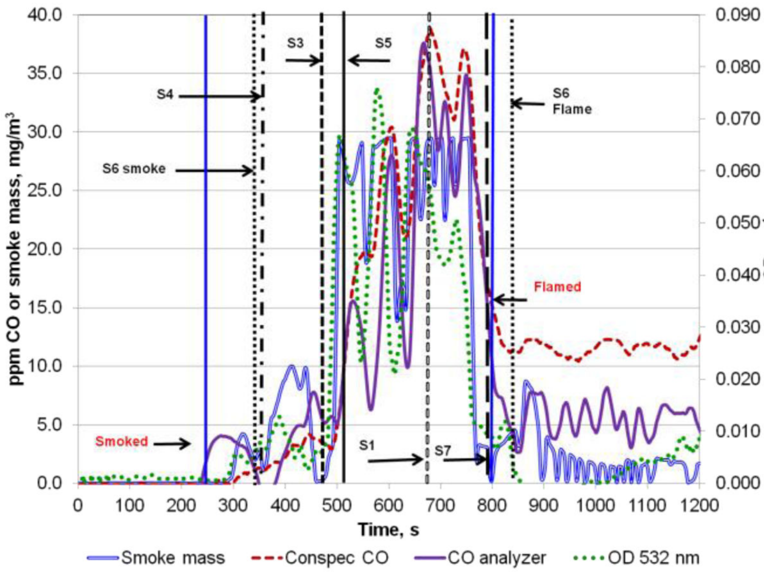

Figure 8.

Comparison of sensor alarms to smoke and CO concentrations for Red oak-2.

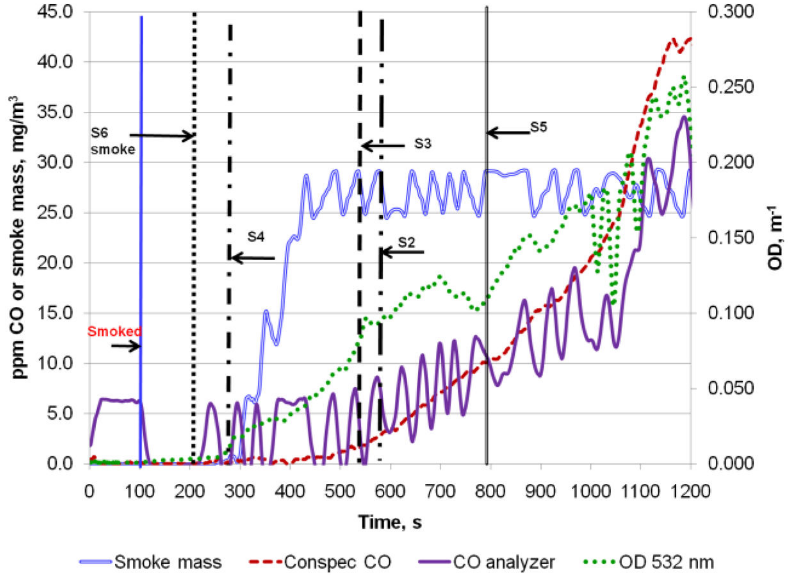

Figure 9.

Comparison of sensor alarms to smoke and CO concentrations for PVC belt.

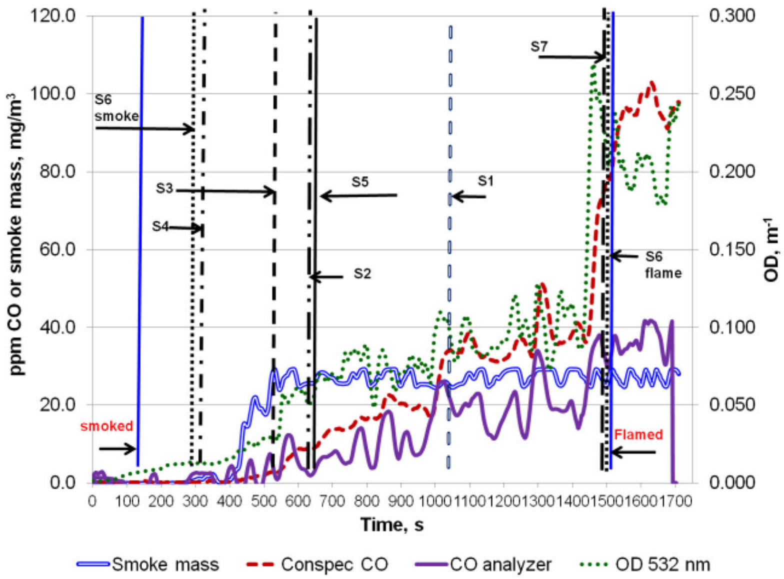

Figure 10.

Comparison of sensor alarms to smoke and CO concentrations for SBR belt-2.

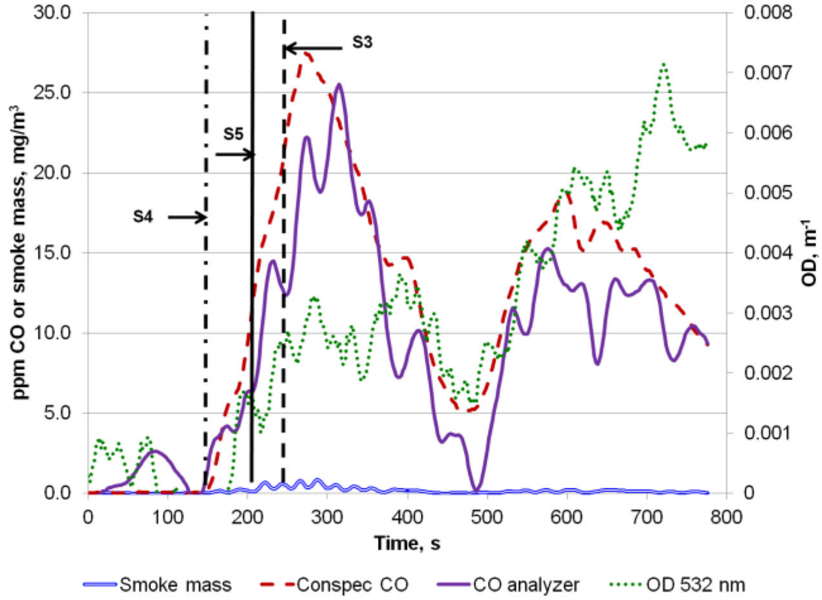

Figure 11.
Comparison of sensor alarms to smoke and CO concentrations for diesel exhaust.

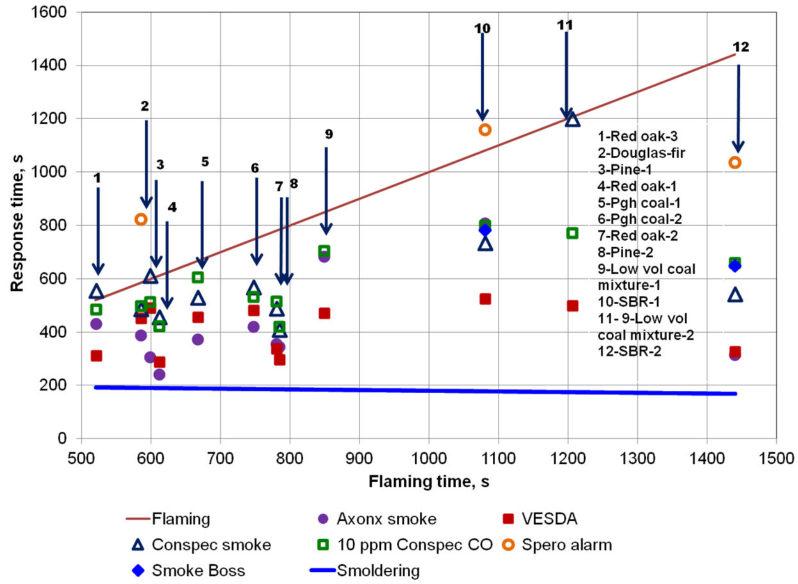

Figure 12.

Performance of the sensor alarms with respect to smoldering and flaming fires.

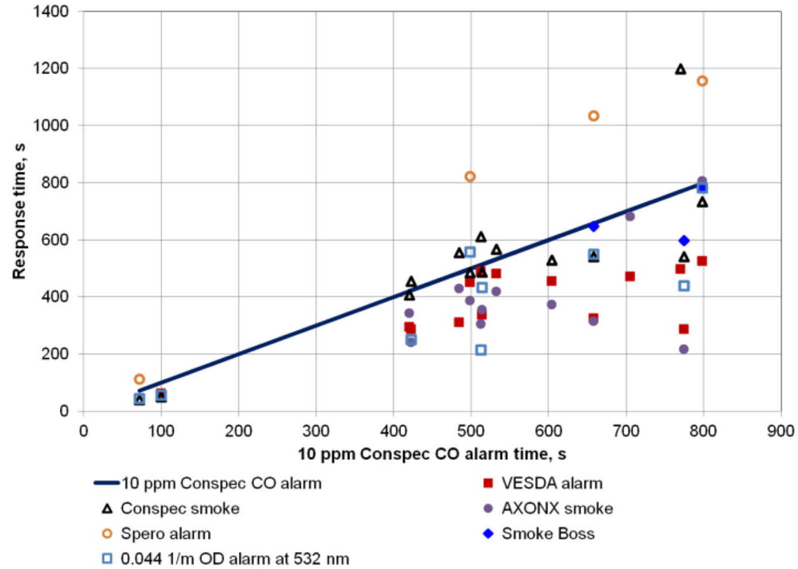

Figure 13.
Comparison of the sensor responses to 10 ppm CO alarm time.

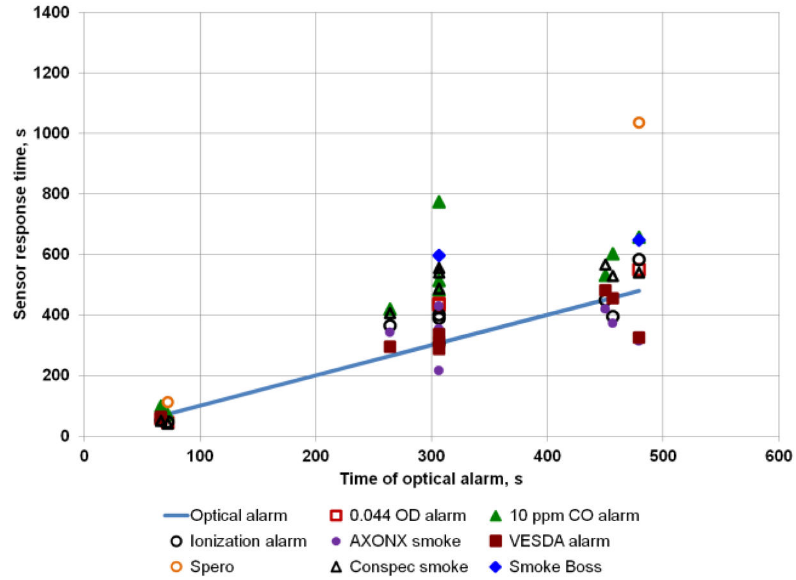

Figure 14.

Smoke and CO sensor responses with respect to UL-approved combination photoelectric/ ionization smoke sensor responses.

Table 1

Smoke, flame, and CO alarm times for the sensors studied

Burning material	Time to visible smoke, min	Time to visible flame, min	Smoke sensor time to alarm, min							CO sensor time to alarm (10 ppm), min	
							UL-approved combination smoke sensor				
			Spero	Smoke Boss	Conspec smoke	VESDA	Optical	Ion	AXONX video smoke	Conspec CO	Bulk Average CO
Douglas-fir	2.50	9.75	13.70	No alarm	8.10	7.53	N/A	N/A	6.46	8.30	8.23
Ponderosa pine-1	3.30	9.97	No alarm	No alarm	10.20	8.17	N/A	N/A	5.10	8.53	7.73
Ponderosa pine-2	3.66	13.08	No alarm	No alarm	6.80	4.93	4.40	6.10	5.73	7.00	5.23
Red oak-1	3.02	10.20	No alarm	No alarm	7.60	4.80	N/A	N/A	4.02	7.03	6.50
Red oak-2	3.88	13.00	No alarm	No alarm	8.13	5.63	5.10	5.10	5.92	8.57	6.90
Red oak-3	2.92	8.68	No alarm	No alarm	9.27	5.20	5.10	6.70	7.17	8.07	6.80
Pittsburgh seam coal-1	3.08	11.12	No alarm	No alarm	8.83	7.60	7.60	6.60	6.22	10.07	9.37
Pittsburgh seam coal-2	3.08	12.45	No alarm	No alarm	9.47	8.03	7.50	7.50	7.00	8.87	8.10
Low vol coal mixture-1	3.10	14.15	No alarm	No alarm	N/A	7.86	No alarm	9.83	11.36	11.76	10.53
Low vol coal mixture-2	3.03	20.10	N/A	No alarm	20.06	8.33	N/A	N/A	N/A	12.83	N/A
SBR belt-1	3.13	18.00	19.30	13.30	12.23	8.77	N/A	N/A	13.46	13.30	11.00
SBR belt-2	2.30	24.00	17.26	10.80	9.03	5.43	7.98	9.73	5.25	10.97	9.57
PVC belt	1.92	N/A	No alarm	9.96	9.03	4.80	5.10	6.50	3.63	12.90	12.83
Diesel fuel-1	N/A	0.50	N/A	No alarm	0.87	1.07	1.10	0.90	N/A	1.67	2.07
Diesel fuel-2	N/A	0.50	1.90	No alarm	0.70	1.07	1.20	0.80	N/A	1.20	1.17
Diesel exhaust	N/A	N/A	N/A	No alarm	4.03	2.23	No alarm	3.50	No alarm	4.36	4.63

N/A- Not available